

CONCEPT-DEVELOPMENT OF A STRUCTURE SUPPORTED MEMBRANE FOR DEPLOYABLE SPACE APPLICATIONS - FROM NATURE TO MANUFACTURE AND TESTING -

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ABSTRACT

Current space applications of membrane structures include large area solar power arrays, solar sails, antennas, and numerous other large aperture devices like the solar shades of the new James Webb Space Telescope. These expandable structural systems, deployed in-orbit to achieve the desired geometry, are used to collect, reflect and/or transmit electromagnetic radiation. This work, a feasibility study supporting a diploma thesis, describes the systematic process for developing a biologically inspired concept for a structure supported (integrated) membrane, that features a rip stop principle, makes self-deployment possible and is part of an ultra-light weight space application. Novel manufacturing of membrane prototypes and test results are presented for the rip-stop concepts. Test data showed that the new membrane concept has a higher tear resistance than neat film of equivalent mass.

1. INTRODUCTION

There is a wide range of applications for thin membrane systems often referred to as Gossamer structures. These large-area apertures like solar sails, sunshields, large antennas, inflatables, photovoltaic arrays etc. are used for energy supply and communication as well as maneuvering of satellites. Key performance metrics of gossamer structures are their large geometric dimensions with low mass/area (areal density) and packaging into a small volume for launch and transit. For economic reasons, the launch mass and packaged volume of these space systems have to be as low as possible, and the durability as well as the damage tolerance need to be high to achieve the design service life. To reach these goals, new concepts need to be developed.

Some research to start solving the membrane durability problem has been performed based on a concept of a membrane with an applied structure, both providing structural support and rip-stop ability at the same time. One essential aspect to consider was the fact that these systems and their very thin membranes have to withstand the space environment, especially micro-meteoroids and orbital debris (MMOD), which can

produce damage as punctures or tears, which can propagate under load and eventually destroy the complete membrane. To tolerate damage and to prevent a total loss of the application, rip-stop, used to stop tearing or crack propagation, usually involves adding fibers, fabrics, tapes and other principles [1]. These approaches add non-structural mass to the membrane. The idea of using the load carrying structure as a rip-stop device and vice versa, as nature does very successfully, seems to be a promising way for mass savings, localizing damage and preventing cracks from propagating at the same time.

Another feature of applying structure to the membrane that saves mass is to make the membrane self-deploying. Although researchers have developed several membrane deployment principles like coilable booms, electro-mechanical mechanisms and/or inflation, here again nature delivers inspiring examples of self-deploying thin film structures.

One of the most challenging aspect of realizing a structure supported membrane is the manufacturing of Gossamer structures. Due to the large and delicate membrane, which is difficult to handle without inflicting damage, joining with the load carrying structure is quite challenging. This aspect was addressed at an early stage of the current study. The manufacturing process and technology can be seen as an integral part of the whole concept and was moreover necessary for producing specimens of the proposed rip-stop approach. This process was realized, using an additive manufacturing method, applying the delicate structure on the film. Since very large structures are to be addressed in the future, large segments of structure supported film should be producible in order to reduce costs.

The following sections describe the systematic process for developing and manufacturing a biologically inspired structure supported membrane. Specimen test data showed that the new membrane concept is easily fabricated and produces better performance than plain films.

2. CONCEPTION

To realize a concept for a damage tolerant membrane structure, the focus was set on finding a new solution for a rip-stop principle and at the same time adding structural stiffness to the membrane. Advances in manufacturing technology were necessary for realization of the rip-stop principle in thin membranes. Some remarkable mechanisms in nature and a brief systematization of possible particular solutions are described in the next subsections.

2.1 Mechanisms in Nature

Ultra-light weight structures, referred to as Gossamer structures, originate in nature as one can find for example on insect wings, feathers, spider webs, leaves and airfoils like bat wings. Several interesting and applicable principles were viewed for idea generation during the conceptual phase of this work.

2.1.1 Ultra-light membrane areas

Thin durable membrane structures can be found in nature from leaves and insect wings consisting in general of a hierarchical structure of veins and membrane. While leaves are in most cases built up symmetrically from central primary veins to secondary and tertiary veins, an insect wing is not symmetrically stiffened [2]. The veins provide the primary structural support for the wings, thicker surrounding structures provide stiffness (leading and trailing edge), and thinner intermediate structures provide less stiffness and eventually perform some damage tolerance. The membrane is the primary aerodynamic structure of the wings. On dragonflies for example the membrane is very thin, with a thickness of only 2 to 3 μm [3]. Typical vein structures in nature are shown in Figure 1 and Figure 2.

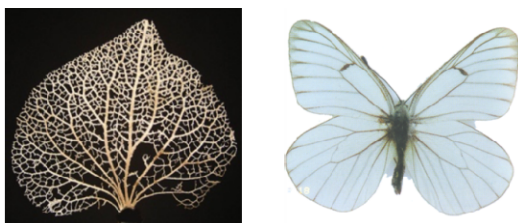


Figure 1. Vein structure of a leaf, a butterfly wing [5]

2.1.2 Damage tolerance

Damage tolerance can be seen particularly on dragonflies. As stated in [4], most major groups of dragonflies display natural wing damage ranging from minor tattering to the loss of large wing sections, especially towards the trailing edge and wing tips. It was also found that a loss of up to 30% total wing area influenced flight behavior but still enabled the insects to

fly. This indicates some rip-stop quality as the damage must have been localized and only a few cases were reported as resulting in the inability to fly. Similar results were reported for bumble-bees and butterflies where the wing damage (15–20% area loss) displayed no difference in flight activity or recapture probability in the wild during flight and aerodynamical loads, thus again indicating some damage tolerance and rip-stop ability. Damage tolerance could also be presumed by observing the wing structure as thicker membrane boundaries (veins). This feature is already in use for rip-stop in current membrane applications e.g. welded seams on the James Webb Space Telescope's sunshade.

One interesting characteristic to note about a dragonfly wing is that there are several different kinds of patterns present in the wing vein framework. The leading edge consists primarily of rectangular frames whereas the trailing surface is largely formed of hexagons and some other polygons with more than 4 sides as discovered in [3]. The hierarchical vein structure with the typical vein pattern of a dragonfly is depicted in Figure 2.



Figure 2. Hierarchical vein structure with the typical vein pattern of a dragonfly [Identification: Dragonfly , 28 August 2010

http://www.flickr.com/photos/joi_698898343/

2.1.3 Deployment

Self-deployment mechanisms can be found in leaves due to their structure. In order not to break when a strong wind is blowing across a leaf, many thin leaves behave elastic and roll up as found in [5]. From winged insects it is known, that when they transform into the adult stage, they use pressurization (inflation) to expand the wings from short stubby highly folded bags into long thin stiff membranes.

Unfolding of wings in adult insects is basically achieved and controlled from the wing base, whereas folding in most cases is possible only by using additional structures, like forewings and abdomen. However, an unfolding supporting intrinsic elastic mechanism within the wings was found to demonstrate self-deployment in several beetle species (Coleoptera) in [6]. Elastic hinges used in returning movements are also known from the

jumping mechanism of fleas.

One remarkable example showing intrinsic elastic mechanisms is the earwig bug. It's venation and folding pattern is unique amongst insects. A schematic view of the hind wing structure displaying veins, elastic joints, fold lines and resilin concentration (a rubber like protein; blue areas) and an earwig bug unfolding one of the wing pair with its cerci is depicted in Figure 3. If the hind wing folds automatically due to intrinsic elasticity, then it must be kept unfolded during flight by some mechanism capable to withstand the aerodynamic forces according to [7].

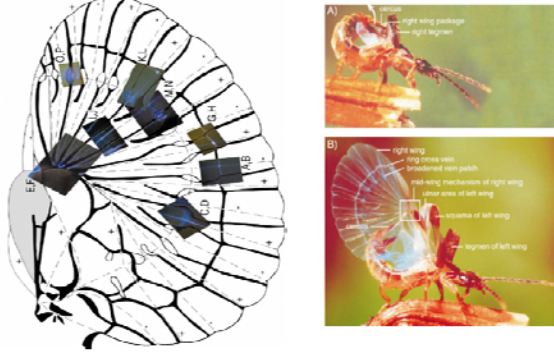


Figure 3. Earwig bug: wing structure and unfolding a wing pair [7]

2.2 Systematization and Principles

To realize a systematic approach for a new concept design, all relevant principles and ideas had to be systemized and categorized to find an appropriate solution covering all requirements and objectives. This was done in a morphological box, a matrix where all applying principles of space applications, physics, nature and common technical understanding feasible for the concept are categorized in subareas or sub-problems.

Ideas and principles were sorted in the matching sub-area to give a systemized overview and to allow a combination of principles or new idea generation for design of the concept. Sub-areas for example were named "Stiffening Structure", "Packaging Methodology", "Membrane Material", "Rip Stop Test Type" or "Manufacturing" to mention some.

3. FINAL DESIGN

3.1 Design of Rip-Stop Specimens

Six series of specimens have been designed and built as shown in Figure 4. In general the specimens were designed to show the ability of added hierarchical structures to exhibit rip-stop at various orientations. The hexagonal and elliptical specimens show an increase in hierarchy and complexity. Closed cells were used to study the ability of the added structure to halt a tear completely. Using the manufacturing process described below, almost any geometry and thickness of the added structures can be realized making this a versatile tool for optimized design.

4. MANUFACTURING

All specimens were made of isotropic casted polycarbonate film, Makrofol N® grade (Bayer®), with a thickness of 0.02 mm (0.8 mil). All applied structures were made of polycarbonate as it is the build material of the applied fused deposition manufacturing (FDM) process and has been selected in the conceptual design phase.

A STRATASYS® FDM 400 mc 3D production system, a fused deposition modeling technology (FDM), was used. This additive manufacturing method was used to print the rip-stop structure, a polycarbonate, directly onto the polycarbonate film.

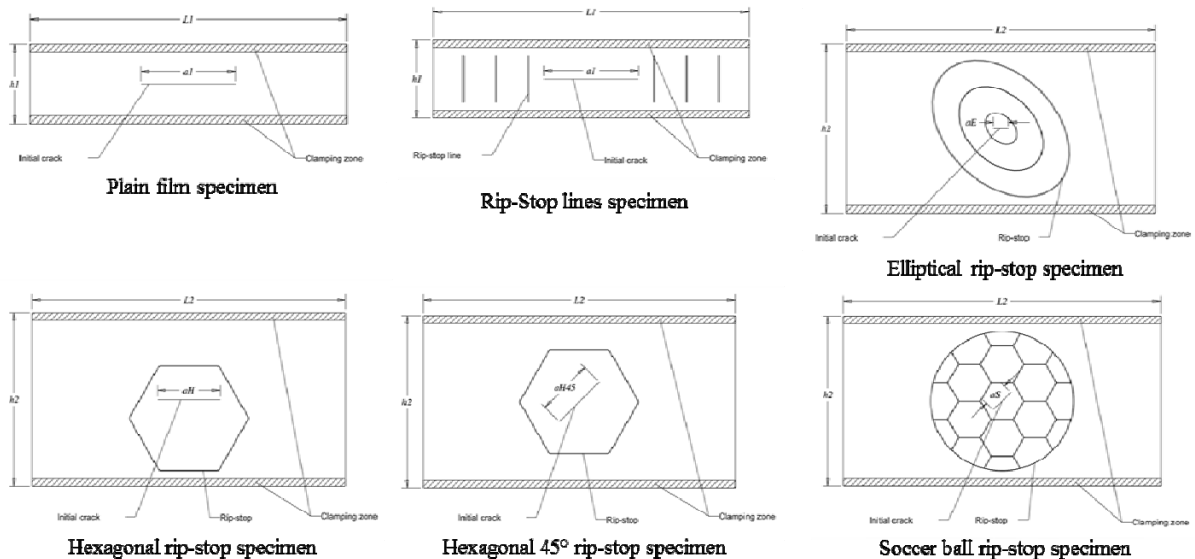


Figure 4. Rip-Stop specimens

Finished specimens were overall very planar and exhibited only minor wrinkles, hardly to be visible to the naked eye, around to the rip-stop structures. A strong bonding, due to fusion, was observed. Peeling the structure off of the film was impossible; instead the film would tear first.

5. EXPERIMENTAL

5.1 Rip-Stop Experiments

A so called bi-axial stress test, see Figure 5, technically a uniaxial tensile test, to measure the load over displacement and to show visually the crack propagation behavior for the rip-stop concepts, was performed. The recorded load curves were to show the effectiveness of the structure as a rip-stop feature. The procedure also used video imaging to detect crack growth, to monitor the overall behavior of the film specimens under load and to record the current load at any crack propagation. The testing methods, procedure and results are outlined in this chapter.

The applied test method was adopted and modified from the works dealing with fracture toughness of thin polymer films done in [8] and [9]. Similar tests using center cracked specimens have already been used for sheet metal in the 1970s [10], for example the ASTM STP 486, and ASTM Method B646-78. The proposed test method has been chosen as it can be related to real damage and tear propagation in large membrane structures such as in solar sails caused by MMOD. This is well represented in the tests explained in this work, using an initial center crack.

The edge load test, described in this paper, is used to generate a load-displacement-curve rather than detecting the fracture toughness with the J-integral theory in contrast to [8] and [9]. The test scheme with the resultant force F , applied as the load to the film perpendicular to the center crack, the film extension U , shown in Figure 5, are measured. The crack propagation as well as the stretching and wrinkling of the film are captured with video imaging. This is one of the main difference from that used in [8] and [9], as this work is done for the whole specimen instead of only for the initial crack and a small area ahead of the crack tip.

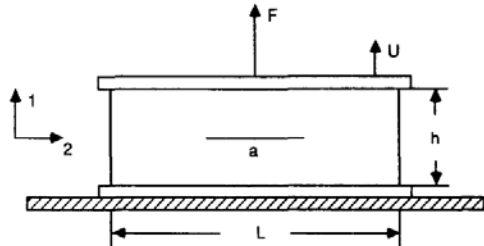


Figure 5. Principle: Bi-axial stress test [Ref.8]

5.1.1 Aim of the Tests, Theory and Expectations

Two main goals were developed for these particular tests. The first was to prove the principle of stopping and pausing the crack propagation for a certain span of loads and therefore increasing the load (extension) taken by the film specimen until the crack propagates through the whole specimen (specimen breaks). As a result several steps, ideally three, for the Rip-Stop lines specimens, if the crack propagation is symmetrical, were expected in the recorded load-displacement curve.

The second aim was to prove the principle of leading/guiding a crack to a different direction by blocking the propagation path with a barrier (rip-stop) standing in an angle to the propagating crack, while the crack is surrounded by a closed rip-stop cell. This should provide another load path (a weaker path) along the rip-stop structure thus leading the crack in another direction off its original path.

A complimentary aim was to combine pausing of the crack propagation and leading the propagation on another load path in a hierarchical structure as it was performed with the Soccer ball specimen to see how a crack propagates from rip-stop cell to rip-stop cell.

For all specimens, results were expected to be seen as steps in the load-displacement curves as a proof of stopping or pausing crack propagation when encountering the angled rip-stop structure seen in the video imaging.

5.1.2 Results and Discussion

As the specimen series within the small specimen type were supposed to prove a basic principle of rip-stop, the Plain specimen series served as a reference without a structure applied. The load-displacement curves for these series show an almost linear slope until the load maximum is reached. A sudden drop of load thus being the event of break follows. The nonlinear section at the very beginning of the curve, at low loads, is owed to the fact that the film specimen had to be stretched before load could be applied. This is true for all specimens tested within this work. These characteristics of the Plain film specimens could be observed on the typical example load-displacement curve shown in Figure 6. For the crack propagation dynamics, a steady pace of crack propagation after the crack opened, followed by the sudden rupture were observed as known from literature [11].

The Rip-Stop lines specimens show the expected steps in the load-displacement curves, thus proving the pausing of crack propagation until a certain threshold is reached. As depicted in Figure 6, three steps in the load-displacement curve, representing three load thresholds of different levels, caused by the rip-stop lines, had to

overcome for the crack to continue propagating. The gain in displacement and maximum load compared to the Plain film specimens are also well represented. Load and crack propagation process was also seen in the video footage. These results show not only that a structure supported membrane is able to stop crack propagation but additionally it proves some redundancy with this hierarchical structure.

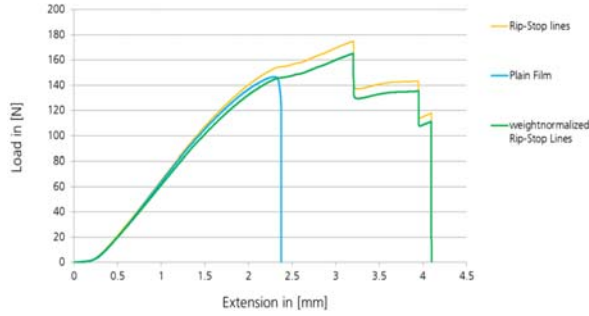


Figure 6. Load-Displacement curves

The weight increase in this case of the Rip-Stop specimens, due to the additional rip-stop structures was about 5% of the mass of the Plain Film specimens, while the increase in maximum load was approximately 22% and 15% for the weight-normalized value.

Essential values of the tested specimens, averaged over the specimen number are shown in Table 1. The values for the specimens of the Large Specimen Type (Elliptical rip-stop specimens, Hexagonal rip-stop specimens, Hexagonal 45 rip-stop specimens and Soccer ball specimens) show the relation that a high mass (weight) indicates a high maximum load and a large maximum extension. But certainly the mass allocation and the structural design plays an important role as well.

Table 1. Essential test values.

Specimen series	Film Thickness [μm]	Weight [g]	Nr. of tests	Max load F_{max} [N]	Max extension U_{max} [mm]
Plain film specimen	21.22	0.37885	6	142.54	2.294
Rip-Stop lines specimen (weight-normalized)	21.22	0.40127	6	173.96 (164,24)	3.564
Elliptical rip-stop specimen	21.22	0.9084	4	264.85	6.183
Hexagonal rip-stop specimen	21.22	0.8097	5	157.06	4.273
Hexagonal 45 rip-stop specimen	21.22	0.83685	5	170.52	4.825
Soccer ball specimen	21.22	0.87388	4	231.99	5.147

From these results and observations, it can be stated that the first Hypothesis “Rip-stop as a structural part of the membrane will stop or pause for a certain load span (threshold) was proved by:

- Rip-stop lines stopped crack propagation resulting in load-displacement curves as steps.
- Rip-stop can turn crack propagation path.
- A crack was kept in a closed rip-stop cell for a certain load span, until a sufficient threshold load was reached. This was proved by the experiments with all specimen series of the Large Specimen Type.
- Crack propagation can be kept within a hierarchical structure was partly proved with the Soccer Ball specimens as the crack was kept within one cell for a certain load span but was not rested again as the crack propagated further. The reason for the sudden rupture of the whole specimen after resting crack propagation or reaching a maximum load and not being stopped by the next structure is due to the high energy release of the abrupt repeated crack initiation as reported in [11].

5.1.3 Self-Deployment Concept

Models of a preliminary concept for the self-deployment tests were created with dimensions inspired by different ratios in the wing of an earwig bug. This design included 5 radiating polycarbonate vein-structures distributed at 30° around a semicircle design. Each vein structure is 165.6 mm (6.52 in) long and comprised an elastic joint; a lens shaped partitioning elastic connection, between two tubular rods as shown in Figure 7.

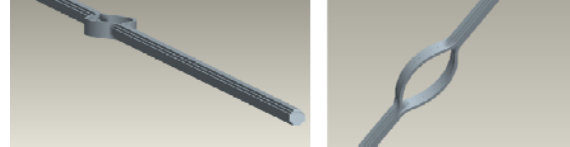


Figure 7. Model detail of the elastic vein.

Since the main focus of this work was developing the rip-stop models, this current self-deploying concept models were not high fidelity and served as proof of concept only. The veins were produced with the fused deposition modeling technology (FDM) process but not printed on film due inadequate bonding on the Kapton film of the ejected polycarbonate build material. Future work is needed to optimize the proposed additive manufacturing for Kapton membranes.

The semi-circle concept for self-deployment, with the bonded veins, was then glued onto the Kapton film. A qualitative test was then performed. The self-deploying model was folded fanwise, at the radiating folding lines between the veins and transversely at the elastic joints towards the center. The folded structure was kept in the

stowed configuration by hand and released. As one can see in Figure 8 the specimen deployed within about 2 seconds to an unfolded configuration. Although the wing-like specimen did not flatten out to the original uncreased state, it was considered to be successfully in proving the concept of using strain energy in the rib structure for self-deployment. More detailed design, better materials and optimized manufacturing would be needed to achieve a high-fidelity self-deploying membrane structure.

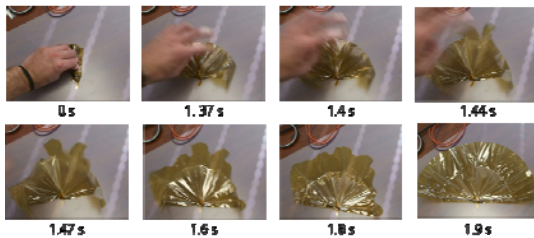


Figure 8. Self-Deployment test.

6. SUMMARY

The systemization of the identified principles were combined into a bio-inspired wing like structure, featuring elastic joints, derived for the self-deployment concept. In addition, six concepts for achieving thin film rip-stop were derived from basic shapes and structures of nature.

The rip-stop specimens were fabricated in a novel direct additive manufacturing approach and then tested in a biaxial stress test with an initial crack. The tests revealed that such rip-stop structures can stop crack propagation for a certain load span when serving as barrier. The principle of a hierarchical structure serving as rip-stop was proved with stepped load-displacement curves. A 15 % mass normalized improvement was measured compared to plain films.

7. FUTURE PROSPECTS

Future prospects for this work can contain concentrations on each of the three foci, rip-stop, self-deployment and manufacturing of a structure supported membrane to develop each technology further. For example, work to create hierarchical rip-stop structures, like the inner wing part of a dragonfly, with elastic micro-joints storing energy for self-deployment without permanent plastic deformations is needed. In addition, roll-to-roll manufacturing processes that apply the hierarchical structure on a ultra-thin film could be envisioned. Future application might be extreme light self-deploying and highly crack damage tolerant systems like solar sails, design like a huge wing of an earwig bug, solar arrays consisting of many wing-like and extreme thin and light panels collecting solar energy.

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